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Geometrical Variation Mode Effect Analysis (GVMEA) for Split Lines

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Abstract

The visual quality is a large contributor to the over-all quality impression of a product. For a complex, assembled product the visual quality is often judged by the geometrical quality in its split lines, where parallel split lines with small gaps and no flush usually are the desirable outcome. The gap, flush and parallelism in the split lines are affected by the variation on part level, variation in the joining process and the design concept itself. The visual sensitivity of a split line is also important in this context, e.g. if a split line is hidden, its visual quality is not important. In this paper, the ideas from traditional failure mode effect analysis (FMEA) are adapted to a geometry assurance context, where the visual impression of split lines is in focus. The visual sensitivity, as well as the probability of non-nominal outcomes, are included in the analysis. The probabilities of non-nominal outcomes are calculated using advanced non-rigid variation simulation based on Monte Carlo simulation combined with finite element analysis. In this way, all forces and bending due to joining and non-nominal geometries can be included. The goal of the suggested geometrical variation mode effect analysis (GVMEA) is to rank the split lines from the most critical one to the least critical one for the visual quality of a product. This is done by calculating a risk priority number for each split line. In this way, the split lines with the highest risk to impair the visual quality of a product can be identified and hopefully fixed. The method is demonstrated on a ready-to-assemble chest, i.e. on an example from the furniture industry.

Keywords: FMEA; GVMEA; Tolerances, Variation simulation; Geometry assurance; Perceived quality; Split lines

1. Introduction

Increased competition in the manufacturing industry puts high requirements on functional, but also aesthetical quality of the final product. An important step in the product development process is to evaluate and value risks in the chosen concept. This paper focuses on the geometry assurance process integrated into the product development process. Geometry assurance refers to the set of activities aiming to reduce the effects of geometrical variation [1]. Geometrical variation in the final product arise due to variation in the manufacturing process of parts, and variation induced during the assembly and joining processes of the parts. Depending on the design concept those variation sources can be suppressed (robust concept) or magnified (sensitive concept). In [2], also time/wear, ambient conditions such as the effect of heat, loading conditions and variation in material properties are mentioned as contributing sources to the total variation in a product.

One of the main tools in the geometry assurance toolbox is variation simulation. Variation simulation will be described more in detail in Section 2.1, but the main purpose is to simulate the variation of a product (as a whole, or in certain dimensions), with variation on part level and variation in the assembly and joining processes as inputs.

Key Characteristics (KCs) is a term to describe the most important features of a product. Already in the early 90's Boeing described the use of KCs for variation reduction [3]. In [4], KCs were defined as geometrical characteristics on the

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product for which small deviations from nominal values have a significant impact on the product. KCs were also discussed in [5]. Howard et al. [6] presented the Variation Management Framework to show a mapping from production variation to the quality loss perceived by the customer for a single characteristic chain. A system capability matrix was used to error sources related to variation in [7].

FMEA (Failure Mode Effect Analysis) is a well-known method to improve products and identify risks, introduced by the US army in 1949. In [8] a literature review of FMEA methods and applications is given. A short summary of the main steps in an FMEA will be given in Section 2.3.

Forslund et al. [9] discuss FMEA for appearance quality from a visual robustness perspective. VMEA (Variation Mode Effect Analysis) is presented in [10] and focuses on the effect of variation sources. It consists of four main steps: (1) Key Product Characteristics (KPCs) breakdown, (2) sensitivity assessment, (3) variation size assessment and (4) variation risk assessment and prioritization. The work in [10] focuses on linking variation in output KPCs to variation in input variables. This can also be done based on the variation simulation model, as presented in this paper, but without the assumption of independent input variables used in [10].

1.1. Scope of the paper

In this paper, a simulation-based FMEA for variation management of split lines is suggested. The breakdown from output KPC and input variables is done based on variation simulation, without limiting distribution or independence assumptions, and the failure probabilities used in the FMEA can be accurately calculated. This procedure is however limited to geometric variation and is called GVMEA (Geometrical Variation Mode Effect Analysis).

In Section 2, background theories for variation simulation, FMEA, and perceived quality are presented. The suggested method is described in Section 3 and applied to a case study from the furniture industry in Section 4. Finally, discussions and a summary are found in Section 5 and 6, respectively.

2. Background

2.1. Variation simulation

Variation simulation, where geometrical variation on assembly level is simulated using Monte Carlo simulation, is one of the most important tools in the geometry assurance toolbox [1]. Nominal part geometries, part tolerances, locating schemes and joining process information are used as input to the simulation. To achieve a satisfactory accuracy for non-rigid parts, the variation simulation must be combined with Finite Element Analysis (FEA) using the Method of Influence Coefficient [11]. In [12] it is shown how the accuracy of a variation simulation for a sheet metal assembly is improved by non-rigid variation simulation compared to rigid simulation. In non-rigid variation simulation, the effect from forces, the joining process, different material and other parameters that can affect the final result can be included [13-17]. The simulation time for large assemblies where Monte Carlo simulation is combined with FEA can be substantial, but there are methods to reduce this using super elements [18].

The most frequently seen application of non-rigid variation simulation is the automotive industry. However, in [19], non-rigid variation simulation for ready-to-assemble (RTA) furniture was discussed. Among the differences between variation simulation for RTA furniture and automotive assemblies, the following ones were identified:

- Material
- Assembly and joining process
- Geometry Assurance Maturity

A method for modeling a certain type of joints for this kind of assemblies was developed [19] and implemented in the software RD&T [20]. The case study described in Section 4 is modeled using this method, and the main steps to predict the geometrical variation of RTA furniture are briefly described below. For a more detailed, technical description, the reader is referred to [19].

Step 1 “Soft fixturing”:

One part, the base part, is positioned (all degrees of freedom are locked). The other parts are “softly” locked to each other and the base part to restrict their degrees of freedom. This is needed for the FEM calculations in step 2. The parts are not bent in step 1.

Step 2 “Joining”:

The parts are joined together using joining elements, for example, the wedge dowels [19] used for the RTA furniture case study in this paper. The positioning in step 1 is overridden and the actual positioning and deformation of the parts are calculated.

Step 3 “Final position”:

The assembled product is positioned in a new locating scheme, physically realized by for example legs in contact with the floor or attached with screws to a wall. Spring back is calculated.

A large number of Monte Carlo replications is run. In each replication, the geometrical deviation of the final assembly (Step 3) is calculated. The result from each replication is stored and in this way, a distribution of the deviation from nominal values can be calculated and measures of variation can be presented.

2.2. FMEA

The major steps in an FMEA are presented here. To get a full introduction to FMEA, the reader is referred to one of the many books on this topic, for example [21].

In FMEA, a risk priority number, RPN, is calculated for each failure mode to conduct the risk assessment. The RPN is the product of the severity factor (S) of certain failure, the occurrence factor (O) for this failure and the detection factor

(D), i.e.

$$RPN = S * O * D \quad (1)$$

Usually, all factors can take values between 1 and 10, and the RPN for each failure mode can be compared to find the most severe ones. The factors can be weighted, as discussed in [22].

2.3. Perceived quality

This work focuses on geometry assurance and failure mode analysis of split lines. Split line quality is an important aspect of the research area of perceived quality (PQ) [23]. In Figure 1 two split lines are visualized. Split line 1 is non-nominal while split line 2 is nominal. As can be seen, the visual quality impression is lowered due to the wide gap and non-parallelism of split line 1.

Figure 1: Example of two split lines.

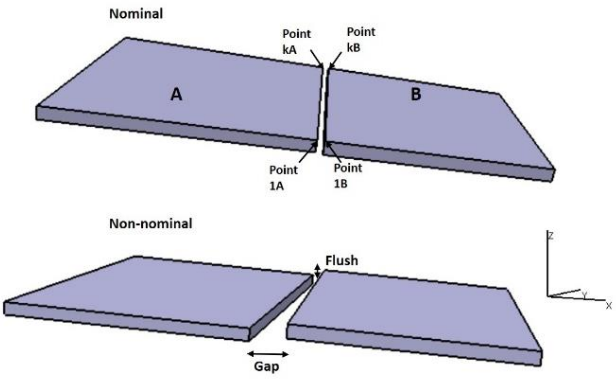

Figure 2: Illustration of flush and gap in a split line.

PQ is a complex, multifaceted area. Understanding quality from the customer's viewpoint and its realization throughout the product development process is important to be able to balance requirements and allocate resources. For this reason, the perceived quality must be understood and controlled during all stages of product development. The Perceived Quality Framework (PQF) [24] provides a framework and a taxonomy that allows customers perception of quality to be described by 32 ground attributes, grouped into nine sensory modalities and related to our 5 human senses – what we see (Visual Quality), what we feel by touching (Tactile Quality), what we hear (Auditory Quality), what we smell (Olfactory Quality) and what we taste (Gustatory Quality). In many product segments, such as the automotive industry, Visual Quality is the most important aspect with around 70% of the total importance. Visual Quality can be decomposed into a number of sensory modalities on the level below. One of these modalities is Geometrical Quality, which is decomposed into four ground attributes; gap, parallelism, flush and reflection alignment. The concepts of gap and flush are illustrated in Figure 2.

Even though the quality of split lines is highly focused in the automotive industry, the problem is the same for all other types of products where a number of components meet to form a spatial relation.

3. Geometrical Variation Mode Effect Analysis (GVMEA)

The GVMEA method suggested in this paper is presented in this section. It is based on the traditional FMEA, but focuses on failure modes related to geometrical quality in split lines and utilizes a non-rigid variation simulation model to calculate the occurrence factors.

As shown in Eq. (1), the RPN in an FMEA is calculated as the product of the occurrence, severity and detection factors. This is also the case in the GVMEA.

3.1. Failure modes

First, it is necessary to define the different failure modes related to the geometrical quality of split lines and how they are evaluated. The failure modes are, as mentioned in Section 2.3, gap, flush and parallelism. Those are measured in the following way, see Figure 2:

- Gap: The gap is evaluated by the distance in the x-direction (in the example) in k point pairs, from 1A/1B to kA/kB
- Flush: As gap, but in z-direction in the figure.
- Parallelism: measured by the angle α between the lines defined by 1A to kA and 1B-kB, i.e.

$$\alpha = arctan(gap_1 - gap_k)/l), \quad (2)$$

where l is the length of the split line.

It can be noted that in the automotive industry, the parallelism requirement is quite often defined in millimeters, measuring the difference between two points. The requirement is then dependent on the length of the split line. Here, the angle defined in Eq. (2) is used instead.

3.2. The severity factor

The severity factor S is calculated based on the severity of a failure mode. In a traditional FMEA, this is judged based on a user perspective and failure modes affecting the security of a product or risking a complete product breakdown are scored high, while minor flaws are scored low. This approach is of course also valid for failure modes related to geometrical variation. For PQ aspects related to split lines, the severity factor *S* should be related to the visibility of a certain deviation. For example, if a split line with low geometrical quality is very visible to the customer it is much more severe than if that split line is partly hidden or normally not in the field of view of the customer. The length of a split line can also affect the severity. This needs to be evaluated from case to case. Values of *S* related to split line visibility are suggested in Table 1.

Visibility of split line	Value of *S*
Hidden to customers	1-2
Partly hidden	3-4
Visible if looking for it	5-6
Visible	7-8
Clearly visible	9-10

Table 1: Severity factors.

3.3. The occurrence factor

The occurrence factor *O* is calculated based on the variation simulation. For a certain dimension *X* on the product or subassembly the occurrence probability, P_o, that *X* is outside the upper specification limit (USL) or lower specification limit (LSL) with an amount δ can be calculated, i.e. P_o=P{*X*<LSL-δ}+P{*X*>USL+δ}. By a variation simulation, following the steps in Section 2.1 this probability is calculated. For simplicity δ=0, i.e. all outside specification occurrences are treated equally.

Probability of occurrence, P_o	Value of *O*
0.5	10
0.125	9
0.050	8
0.025	7
0.0125	6
0.0025	5
0.0010	4
0.0003	3
0.0001	2
10^-6	1

Table 2: Occurrence factors, from [25, 26].

For gap and flush, the values in a split line are sampled from the variation simulation every 5th millimeter using the seam of variation method described in [27]. An example of a seam is color-coded in Figure 4. The value of P_o for a split line is based on the worst-case for each split line, i.e. if any of the sampled values from a split line is outside specification, the split line is considered as out of specification.

The probability of occurrence P_o must be translated to a value of *O*. There are different approaches for this, but here the version used in [25], originally from [26] is employed. The translation table is shown in Table 2.

3.4. The detection factor

The detection factor is related to the probability of detecting a failure before the product goes to the customer. This probability is, of course, related to the quality control system used.

In statistical process control, control charts are used to monitor the process and detect if the process is out of control due to new sources of variation. If samples of size *n* are taken on a regular basis, a *xbar*- and an *r*-chart can be used to control group mean and range, respectively [28]. For those kinds of charts, it is possible to calculate the average run length (ARL) given a certain deviation δ [28]. The ARL values for different failure modes would be possible to use to calculate the detection factor *D*. It should, however, be noted that most control charts are based on the assumption of normal distribution, which is not a necessary assumption for neither the variation simulation or the severity analysis.

However, usually, the quality control plan is the same for the different failure modes related to the PQ related requirements in geometry assurance, and therefore, the value of the detection factor *D* is kept constant in this paper.

3.5. Overall RPN

Since *D* is kept constant, the *RPN* for each failure mode *i* reduces to

$$RPN_i = S_i * O_i, i = 1, \dots, k. \quad (3)$$

When RPN_i:s are determined for all failure modes, they can be compared and ranked. In Figure 3 an overview of the workflow can be seen.

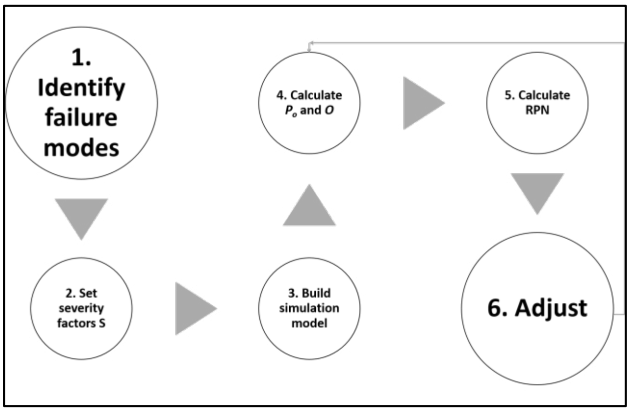

Figure 3: Workflow of GVMEA.

The failure mode with highest RPN value should be adjusted if deemed too high. If the design concept is already established, the severity factor *S* will not be possible to adjust. Therefore, the probability of occurrence P_o, and thereby also *O* (step 4, Figure 3), needs to be reduced. This is affected by the locating schemes, the part tolerances and the joining process (including parameters such as joining sequences and assembly fixture repeatability). Thereafter, the new RPNs can be calculated and the process continues until satisfactory result is achieved.

The most straight forward approach to reduce the P_o value is usually to tighten the tolerances. To find out what tolerance to change, a contribution analysis can be used [1]. Such an analysis ranks all tolerance contributions to a critical dimension based on their influence.

However, split lines associated with the same part will not be independent, i.e. if tolerances affecting one split line is changed another split line will most likely also be affected. By tightening the tolerances, i.e. reducing the allowed variation, all linked split lines will be affected in a positive manner with reduced variation. If an offset is changed, the effects on other split lines need to be carefully investigated using the variation simulation model in order to avoid suboptimal changes with only local positive effects.

Case study

The GVMEA will be applied to a case study from the furniture industry, shown in Figure 4. This ready to assemble chest consists of a frame and three drawers. The dimensions of the frame are 0.60x0.57x0.73 meters. The frame is modeled as a non-rigid assembly and the side panels and the back panel are joined to the top and bottom using 20 fastener elements of two different types. The joining elements are modeled using the method outlined in Section 2.1.

The tolerances on part level, taken from drawings, are:

- Thickness of parts – individual and global (0.1/0.2 mm)
- Position tolerance for joining elements (0.2-0.28 mm depending on the type)

The thickness in two adjacent nodes on a part is probably very similar. Different alternatives to capture this are using the process signature approach [29], a skin model [30] or simply 3D scan data. Without this information, an assumption must be made. Therefore, the thickness tolerance for this case study is partly modeled as a global tolerance giving the same value to all nodes on the same part in each Monte Carlo replication. Each node does however also get its individual tolerance to allow for small, individual, movements.

Furthermore, the floor, whereon the chest is positioned after assembly, is assumed to have a tolerance with range 3 mm.

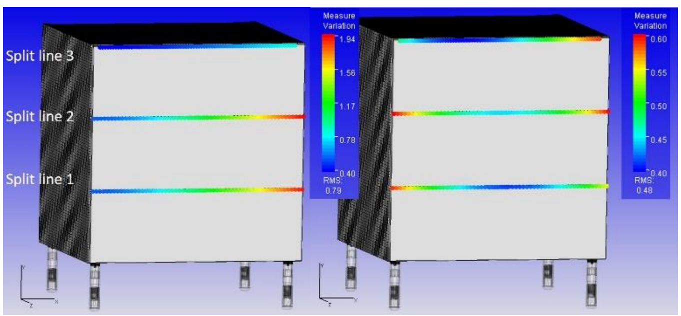

Figure 4: The case study. Color coding of variation in flush (left) and gap (right) direction in the split lines.

The failure modes for the case study is for simplicity limited to three different split lines. The simulated variation in flush and gap directions for the split lines are color-coded in Figure 4.

For each split line, three failure modes are defined related to gap, flush and parallelism. It should, however, be noted that for split line 3, the flush between the top panel and the upper drawer is measured in y-direction and gap in z-direction. For split lines 1 and 2, the flush and gap between the drawers are measured in z- and y-direction (i.e. the opposite). There is also a nominal gap of 3 mm for split lines 1 and 2, while the nominal gap is 0 for split line 3. This makes split line 3 more sensitive for deviations since a deviation from 0 mm is more easily detected than a deviation from 3 mm. Therefore, and also since split line 3 is in the middle of the field of view of a customer, split line 3 get a higher severity score S. Split line 2 is more visible than split line 1, but not as visible to the customer as split line 3. This is reflected in the values of S for the different failure modes, see Table 3.

The values of P_o are calculated using the method explained in Section 2.1 and translated to values of O using Table 2. The software RD&T [20] is employed for compliant variation simulation.

Failure mode	***O***	***S***	***RPN***
Gap 1	9	2	18
Flush 1	6	3	18
Parallelism 1	1	3	3
Gap 2	9	5	45
Flush 2	6	5	30
Parallelism 2	1	5	5
Gap 3	4	9	36
Flush 3	6	9	54
Parallelism 3	1	9	9

Table 3: GVMEA for the case study

The *RPN*-values for the case study are shown in Table 3. This indicates that Gap 2 and Flush 3 are the failure modes most important to focus on in order to achieve a high visual quality from a customer point of view. Based on this, it might be of interest to tighten some of the tolerances contributing to those failure modes. This is especially true for Gap 2, where O has the highest influence on the total *RPN*-value.

4. Discussion

The suggested method is meant to guide engineers when iterating product design requirements and production process solutions with a geometry assurance focus. However, just as in a standard FMEA there are subjective elements. The severity factor can be difficult to judge. One way of doing this is to show different deviations in a virtual model to customers and ask them to grade the severity.

For future work, the detection factor could be integrated with the GVMEA, using a method based on ARL as outlined in Section 3.4 or based on information content in inspection data [31-32]. Furthermore, instead of treating all outcomes inside specifications as equally good, the concept of Taguchi loss functions can be used in the calculations.

5. Summary

FMEA is a standard tool in quality engineering, used to identify potential failure modes in a system and their causes and effects. In this paper, a GVMEA is suggested, focusing on identifying and ranking failure modes for split lines in a geometry assurance context.

The method uses non-rigid variation simulation to calculate probabilities of occurrences and combine this with the visual sensitivity of a split line to achieve a final RPN.

GVMEA can be used in different stages of the product development process to iterate part tolerances and requirements on split lines in stages when the production processes are still under discussion. The method supports identification of split lines that can lead to a low-quality impression from the customer point of view.

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